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APPLICATION FOR U.S. LETTERS PATENT

TITLE:

SYSTEM AND METHOD FOR MEASURING CURRENT

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SYSTEM AND METHOD FOR MEASURING CURRENT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is related to U.S. patent application serial no. [[attorney docket no. 200208754-1 (P742US)]], entitled "METHOD AND SYSTEM FOR CALIBRATION OF A VOLTAGE CONTROLLED OSCILLATOR (VCO);" U.S. patent application serial no. [[attorney docket no. 200208727-1 (P744US)]], entitled "A SYSTEM FOR AND METHOD OF CONTROLLING A VLSI ENVIRONMENT;" and U.S. patent application serial no. [[attorney docket no. 200208728-1 (P745US)]], entitled "A METHOD FOR MEASURING INTEGRATED CIRCUIT PROCESSOR POWER DEMAND AND ASSOCIATED SYSTEM," filed concurrently herewith, the disclosures of which are hereby incorporated by reference herein in their entirety.

BACKGROUND

[0002] Traditionally, a microprocessor's average current draw is monitored by converting analog values of current to digital values that can be used by the microprocessor. This required some form of analog-to-digital (A/D) converter and an averaging circuit. The standard method of measuring current involves sending the current through a known "sense" resistance and measuring the voltage drop across the resistor. The known resistance and measured voltage can be plugged into Ohm's law ($I = V/R$) to calculate the current.

[0003] This method involves the design of an A/D converter for measurement of the voltages on both sides of the sense resistor. Using a discrete, off-die A/D converter to measure the voltage drop requires a separate component that is on or very near the microprocessor package, which increases the microprocessor package cost. Furthermore a separate interface is needed between the microprocessor and the A/D converter, which further complicates the design.

[0004] An alternative design is to put the A/D converter into the package, which would be a very complicated process and is likely to yield relatively inaccurate results in a digital integrated circuit manufacturing process by which the microprocessor is fabricated. The addition of the sense resistor also wastes power by dissipating power in the resistor instead of putting it to useful work in the circuit.

SUMMARY

[0005] An embodiment of the invention is directed to a method for measuring a current in an integrated circuit comprising measuring a first output count from a voltage controlled oscillator (VCO) using a first measurement voltage, measuring a second output count from the VCO using a second measurement voltage, and calculating the current in the integrated circuit using a voltage proportional to a difference between the first and second output counts.

[0006] Another embodiment of the invention is directed to a system for monitoring the current in an integrated circuit comprising an integrated circuit power supply line having a first measurement point and a second measurement point, two voltage controlled oscillators (VCO) having control inputs adapted to be coupled to the first and second measurement points respectively, and counters coupled to the outputs of the VCOs.

[0007] A further embodiment of the invention is directed to a circuit comprising an inverter, a pass gate circuit coupled to an output of the inverter and operating to allow current to flow in an amount proportional to a control voltage, and an amplifier coupled to the output of the pass gate circuit.

[0008] An additional embodiment of the invention is directed to a voltage controlled oscillator (VCO) comprising three stages connected together in a ring, wherein each stage comprises an inverter, a pass gate circuit coupled to an output of the inverter and operating to allow current to flow in an amount proportional to a control voltage, and an amplifier coupled to the output of the pass gate circuit; a control voltage input coupled to the pass gate circuit of each stage; and an output between two of the stages.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIGURE 1 is a block diagram of a CPU incorporating an embodiment of the present invention;

[0010] FIGURE 2 is a block diagram of a prior art ring oscillator;

[0011] FIGURE 3 is a schematic diagram of a single stage of a ring oscillator for use in an embodiment of the invention; and

[0012] FIGURE 4 illustrates a three-stage ring oscillator incorporating the circuit of FIGURE 3.

DETAILED DESCRIPTION

[0013] The present invention uses the microprocessor package resistance as the sense resistor, which results in no additional power loss in the circuit. Instead of using a separate sense resistor, an ammeter according to the invention uses the inherent parasitic resistance in the package. The voltage drop is measured across this inherent package resistance, which eliminates the need for a separate sense resistor and saves both board space and power.

[0014] The present invention also uses an on-die, high-gain voltage controlled oscillator (VCO) and a digital counter instead of a separate A/D converter to perform both magnitude and averaging functions of the voltage measurement. The input port for the voltage measurement circuit is the control port of the VCO. The frequency of the VCO is proportional to the control voltage input. The counter is used to count the frequency of the VCO for a fixed time interval. The control voltage can be inferred from the frequency count through calibration of the VCO circuit. By running the counter over a significant period of time this method also provides average readings over the time interval of interest, thereby saving additional averaging circuitry.

[0015] The invention may use a new high-gain VCO that provides high resolution measurements. The VCO used in one embodiment is a standard ring oscillator that has a novel pass gate at each stage to limit the current at the output of an inverter. This provides greater gain for the VCO, which translates to more accurate measurement resolution in the circuit.

[0016] FIGURE 1 is a block diagram of CPU 100 incorporating an embodiment of the present invention. Microprocessor 101 is constructed on VLSI CPU package 102. Microcontroller 103 is also constructed on VLSI CPU die 102. Microcontroller 103 monitors and controls the VLSI environment to optimize the operation of microprocessor 101. One of the parameters that is monitored and controlled by microcontroller 103 is the CPU's power demand level.

[0017] CPU 100 is designed to operate at some maximum power level. The operating frequency - or the number of instructions that are being processed per second in CPU 100 - is related to the CPU's power level. A higher power level is required for the CPU to operate at higher operating frequencies. Microcontroller 103 monitors the power level and controls the VLSI environment to optimize the power level and operating frequency in microprocessor 101.

[0018] Power supply 104 provides current to microprocessor 101 via power supply grid 105a, 105b. The power demand level for microprocessor 101 can be determined from the current that is provided via power supply grid 105a, 105b. If the current through power supply line 105b is measured, then the power demand for microprocessor 101 can be determined. In an embodiment of the invention, the current through from the power supply is calculated by measuring the voltage drop across line 105b.

[0019] The two VCOs 106a,b are used to monitor the voltages V_A, V_B at either end of power supply line 105b. From these voltages, the voltage drop (V_B - V_A across line 105b can be calculated. Using the inherent resistance R_{PS} of line 105b, the current through line 105b can then be calculated using Ohm's Law ($I = (V_B - V_A)/R_{PS}$). The value of resistance R_{PS} across line 105b must be known to make this calculation. One way to determine inherent resistance RPS is to apply a known current (I_{known}) through line 105b and then measure the voltage drop across line 105b at that current level. Again, Ohm's law can be used to calculate the resistance using those values ($R_{PS} = (V_B - V_A)/I_{known}$). Other methods of and systems for measuring the inherent resistance in the CPU package are disclosed in U.S. patent application serial no. [[attorney docket no. 200208728-1 (P745US)]], entitled "A METHOD OF AND SYSTEM FOR CONTINUOUS ON-DIE AMMETER CALIBRATION TO COMPENSATE FOR TEMPERATURE AND DRIFT ON-BOARD A MICROPROCESSOR," filed concurrently herewith, the disclosure of which is incorporated by reference herein. The use of inherent resistance R_{PS} across line 105b avoids the need to have a separate, discrete resistor component for the current measurements.

[0020] Traditional voltage measurements required the use of an A/D converter to convert the measurements into a digital format that could be used for the power calculations. In the present invention, VCOs 106a,b act as an A/D converter and provides a digital signal representing voltages to microcontroller 103.

[0021] The output of VCOs 106a,b is proportional to the input control voltage. As the control voltage is increased, the output frequency of VCOs 106a,b increases. The output frequency of VCOs 106a,b can be counted over a specified interval using a digital counter. The output count (a digital value) is proportional to the input voltage (an analog value). Therefore, the VCO/digital counter combination acts like an A/D converter.

[0022] Microcontroller 103 may act as the digital counter for VCOs 106a,b. When VCO 106a is connected to input voltage V_A, microcontroller 103 will count a first number of pulses from VCO 106 over the count interval. VCO 106b is simultaneously connected to input voltage VB, and microcontroller 103 also counts a second number of pulses during the count interval. The difference between the two output counts is a digital value that is proportional to the voltage drop across power supply line 105b and that can be used by microcontroller 103 for the current and power calculations.

[0023] The inherent resistance is expected to be a very small value and, therefore the voltage drop across the resistance is expected to also be very small, for example, on the order of 10-20 mV. The VCO must have a high gain so that a significant count difference is generated between voltages V_A and V_B. VCO 106 may be a three-stage ring oscillator that operates at approximately 10 GHz so that a sufficient count difference is generated over an 8 microsecond measurement period.

[0024] FIGURE 2 is a block diagram of prior art ring oscillator 200 in which three inverters 201-203 are connected in series so that signals out of inverter 203 continue to loop back to inverter 201 through line 204. Oscillator 200 generates a constant-frequency output signal at output 205. The design of oscillator 200 can be modified by placing a pass gate at the output of each inverter stage wherein the pass gate limits current flow through the circuit based upon a control voltage. Such a oscillator may be used as VCO 106 in FIGURE 1.

[0025] FIGURE 3 is a schematic diagram of a single stage of a ring oscillator for use in an embodiment of the invention. Circuit 300 consists of three parts: inverter 301, pass gate 302 and amplifier 303. Inverter 301 consists of PFET transistor 304 and NFET transistor 305, which are configured to invert input signals at node 306 so that an inverted signal is output to node 307.

[0026] Circuit 300 includes novel pass gate 302, which functions to limit the current that flows through the circuit. Pass gate 302 consists of NFET 308 coupled to the input control voltage V_{IN} and PFET 309 is coupled to an inverted control voltage V_{INb}. As control voltage V_{IN} increases and inverted control voltage V_{INb} decreases, transistors 308 and 309 are more "on" which allows more current to pass from node 307 to 310. This means that as V_{IN} increases and V_{INb} decreases, circuit 300 will switch at a faster rate. Amplifier section 303, consisting of PFET

311 and NFET 312, amplifies the signal from pass gate 302 at node 310 to the output of circuit 300 at node 313.

[0027] Circuit 300 can be used to replace the individual inverters 201-203 of FIGURE 2 to form three-stage VCO 400 as illustrated in FIGURE 4. Oscillator 400 will produce output pulses at a set frequency at 401 for a particular input voltage V_{IN}. As the voltage V_{IN} is increased, more current flows through each stage 300 and the transistors in each stage switch at a faster rate, which causes the output signal at 401 to increase in frequency. Likewise, if the control current V_{IN} is decreased, then the output frequency count decreases at 401.

[0028] Oscillator 400 can be used as VCO 106 (FIGURE 1) wherein the voltages from measurement points V_A and V_B are applied as input voltage V_{IN}. The output signal 401 is then counted by microcontroller 103, for example, for a set measurement interval, such as 8 microseconds. In one embodiment, oscillator 400 operates at approximately 10 GHz and has a gain on the order of 20 GHz/Volt. These parameters are expected to provide a sufficient difference in counts at measurement points V_A and V_B across inherent resistance R_{PS} so that a voltage drop can be detected and quantified for use in the current and power calculations.

[0029] It will be understood that although the VCO described herein is used to measure the current drawn by a microprocessor, the present invention can be used to measure voltages and current in any integrated circuit.